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RESEARCH REPORT

A self-referential default brain state: patterns of coherence, power, and eLORETA sources during eyes-closed rest and Transcendental Meditation practice

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Abstract Activation of a default mode network (DMN) including frontal and parietal midline structures varies with cognitive load, being more active during low-load tasks and less active during high-load tasks requiring executive control. Meditation practices entail various degrees of cognitive control. Thus, DMN activation patterns could give insight into the nature of meditation practices. This 10-week random assignment study compared theta2, alpha1, alpha2, beta1, beta2 and gamma EEG coherence, power, and eLORETA cortical sources during eyes-closed rest and Transcendental Meditation (TM) practice in 38 male and female college students, average age 23.7 years. Significant brainwave differences were seen between groups. Compared to eyes-closed rest, TM practice led to higher alpha1 frontal log-power, and lower beta1 and gamma frontal and parietal log-power; higher frontal and parietal alpha1 interhemispheric coherence and higher frontal and frontal-central beta2 intrahemispheric coherence. eLORETA analysis identified sources of alpha1 activity in midline cortical regions that overlapped with the DMN. Greater activation in areas that overlap the DMN during TM practice suggests that meditation practice may lead to a foundational or 'ground' state of cerebral functioning that may underlie eyes-closed rest and more focused cognitive processes.

Keywords Coherence · Power · LORETA · Transcendental Meditation · Alpha · Beta1

Introduction

A default mode network (DMN) including medial frontal cortices, the anterior cingulate, the precuneus and the lateral parietal cortices was first noted when comparing data from nine different neural imaging studies, in which unrelated and independent tasks all led to *decreases* in the DMN (Raichle et al. 2001). DMN activation is higher during low cognitive load periods and is lower during goal-directed behaviors requiring executive control (Gusnard et al. 2001; Raichle and Snyder 2007). DMN activation is also higher during self-referential mental activity (Gusnard et al. 2001; Vogeley et al. 2001; Kelley et al. 2002); higher during tasks involving self-projection—mentally projecting oneself into alternative situations such as envisioning the future (prospection); higher when considering the viewpoint of others (theory of mind) (Buckner and Carroll 2007); and higher when attending to stories containing either 1st or 3rd person pronouns (Decety et al. 2002; Kjaer et al. 2002). The DMN has been defined as an intrinsic, default property of the brain (Fox and Raichle 2007).

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In general, DMN activity varies with level of cognitive load. Baseline states with progressively increasing cognitive load, such as eyes-closed rest, eyes-open, and eyes-open simple fixation, resulted in progressive decreases in DMN activity (Yan et al. 2009). An fMRI study comparing implicit and explicit memory tasks reported higher DMN activity during implicit memory tasks and lower DMN activity during explicit tasks (Yang et al. 2009). Comparing subjective reports of stimulus independent thought or "mind-wandering" and DMN activity, researchers reported that more frequent mind-wandering was associated with increased DMN activation (Mason et al. 2007). Using an "experience sampling" technique, periods immediately before mind-wandering probes were preceded by higher blood flow in the DMN as well as in executive network regions—dorsolateral prefrontal cortex and dorsal anterior cingulate (Christoff et al. 2009). In addition, activation in both of these areas was highest when subjects were not aware of their mind-wandering. Thus, the DMN may be involved in the generation of spontaneous cognition–daydreams or stimulus independent thought–as well as the functional organization of information processing (see Raichle and Snyder 2007).

Decreasing DMN activation with increasing cognitive load suggests that DMN activation levels could index mental processing along an object-referral/self-referral continuum (Travis et al. 2004). DMN activation would be lower during object-referral experiences including focused attention on tasks in which the object of experience is primary and self-awareness is secondary. DMN activation would be higher during self-referral experiences and self-projective tasks in which self-awareness is primary and objects of experience are secondary.

Activity in different EEG bands is associated with DMN activation levels. Higher frontal−central theta power correlates negatively with DMN activity as measured by fMRI during working memory tasks (Yan et al. 2009) and during natural fluctuations in theta power during eyes-closed rest (Scheeringa et al. 2008). Higher posterior alpha power during a modified Sternberg task also correlates negatively with DMN activity—explained as active inhibition of brain areas that may interfere with a memory task (Scheeringa et al. 2009).

Meditation practices entail various degrees of cognitive control. Thus, EEG and DMN activation patterns could give insight into the nature of meditation practices. For instance, Zen meditation creates states of self-awareness with reduced conceptual content through disciplined regulation of attention, breath, and bodily posture (Pagnoni et al. 2008). During Zen meditation, midline frontal theta power and sympathetic activity are reported higher (Kubota et al. 2001).

In contrast to concentration meditation techniques, the Transcendental Meditation technique leads to states of self-awareness with reduced conceptual content through minimal, if any, cognitive control. TM practice is characterized by periods of spontaneous respiratory suspension of 10 sec or longer (Farrow and Hebert 1982; Badawi et al. 1984; Travis and Wallace 1997), reduced sympathetic activation (Dillbeck and Orme-Johnson 1987; Travis et al. 2009) and increased parasympathetic activation (Travis 2001) along with increased frontal and central alpha1 power (Banquet 1973; Hebert and Lehmann 1977; Orme-Johnson and Haynes 1981) and frontal alpha coherence during TM practice compared to eyes-closed rest (Dillbeck and Bronson 1981; Gaylord et al. 1989; Travis and Wallace 1999; Travis and Arenander 2006). MEG Localization algorithms identify sources in medial prefrontal and anterior cingulate cortices during TM practice, corresponding to higher alpha frontal power during the practice (Yamamoto et al. 2006). Physicists have suggested that the state of de-excitation of mind and body during TM practice and its relation to ongoing mentation may be analogous to ground states observed in physical systems and their relation to more excited states of the system (Hagelin et al. 1999). It is thus of interest to examine the pattern of activation of the DMN during TM practice as reflected in a variety of EEG parameters.

The 10-week random assignment study reported here investigated longitudinal changes in EEG power, coherence, and eLORETA sources of activation during TM practice compared to eyes-closed rest. This is the first report of eLORETA patterns during TM practice providing an initial approximation of cortical sources of surface EEG activity. The hypotheses tested in this study were that TM practice would be characterized by (1) higher frontal alpha1 power and coherence; (2) lower beta1, beta2, and gamma power and coherence; (3) no group differences in alpha lateral asymmetry; and (4) distinct cortical sources of EEG identified by eLORETA during TM compared to eyes-closed rest that would overlap the DMN.

Method

Subjects

Pretest data were recorded from 50 university students (13 males and 37 females; average age = 22.4 ± 8.0 years) at the beginning of the Spring 2006 semester. The students responded to signs advertising the research. Following baseline EEG recordings, students were randomly assigned, using computer randomization, to either TM or control groups.

The posttest occurred 10 weeks later, which was before the final's week at the end of spring semester. Final's week is a time of maximum stress for students. Six students from each group did not come in for post testing. This resulted in 38 students in this study with 14 females and 5 males in the experimental group (25.0 ± 11.2 years old) and 15 females and 4 males in the control group (20.7 ± 4.9 years old). The 7 men and 5 women (21.2 ± 5.61 years old) who dropped out of the study are discussed in the results section.

Procedure

Students came in for pretest and posttest EEG recordings during the afternoon. Thirty-two EEG active-sensors were applied according to the 10/10 system using the BIOSEMI ActiveTwo system (http://www.biosemi.com). Potentials at the left and right ear lobes were also measured for calculating a linked-ears reference offline.

Following sensor application, EEG was recorded at 256 samples/sec during two computer reaction time tasks, and then during 10 min eyes-closed rest. During eyes-closed rest, students were instructed to "Just sit easily, not minding anything." Following pretest recording, students were randomly assigned to TM or control groups. TM instruction involved two introductory lectures (1 h each), a personal interview with a certified TM teachers, personal instruction on 1 day (1 h), and three group meetings on the three following days (1 h each). The TM individuals practiced TM in their rooms for 20 min twice a day for 10 weeks. Students filled out a compliance form at posttest. The TM individuals practiced 89% of possible TM sittings in the 10 weeks. Over the 10 week period, the TM subjects came in for five individual meetings (20 min) to check the meditation process. Also, optional monthly meetings were available to discuss experiences during meditation.

At posttest, 10 weeks later, all students were again given the two computer reaction-time tasks and a final 10-min resting session. At the posttest, the final 10-min session was TM practice for the experimental group and eyes-closed rest for the control group. The experimenter was blinded to group membership at recording[1] and during data analysis. The data recorded during the computer tasks are reported elsewhere (Travis et al. 2009).

Intervention: the Transcendental Meditation technique

The TM technique is a mental procedure practiced sitting comfortably with eyes closed for 20 min morning and afternoon. Superficially, TM practice can be described as "thinking" a mantra and going back to it when the mantra is forgotten. More accurately, TM practice is a process of transcending—appreciating the mantra at "finer" levels in which the mantra becomes more secondary in experience and ultimately disappears and self-awareness becomes more primary (Maharishi Mahesh Yogi 1969; Travis and Pearson 2000). Unlike most mantra meditations, the mantras used in TM practice have no meaning; they are not labels of objects or concepts, but are used for their "sound" value. The sound of the mantra is such that the attention easily and automatically attends to it without effort or concentration, and as the perception of the sound readily refines, the mind transcends. Even if there may be incidental associations with the sound of the mantra, these are not part of TM practice. Also, most mantra meditations involve either contemplation—thinking about the meaning of the mantra, or they involve concentration—keeping the mantra clearly in mind during the meditation period and/or relating the mantra to a physiological rhythm such as the breath. TM does not involve contemplation, concentration, control, or manipulation of the mind. Rather, TM practice is described as an automatic process of transcending (Maharishi Mahesh Yogi 1969).

Cognitive psychology classifies a task as automatic, if performance on the automatic task is not affected by adding a secondary task and is not affected by increasing task loads (Schneider et al. 1994). TM becomes automatic not through extensive practice, but because it uses the "natural tendency of the mind" to transcend (Maharishi Mahesh Yogi 1969). The automatic nature of transcending during TM practice is reflected in the fact that there is not a novice/expert dichotomy with TM practitioners as has been reported in other meditation traditions (Brefczynski-Lewis et al. 2007). For instance, a 1-year longitudinal study (Travis and Arenander 2006) and two cross-sectional studies—comparing individuals with 4 months' versus 8 years' TM practice (Travis 1991) or individuals with 7 years' versus 32 years' TM practice (Travis et al. 2002)— report that brain wave patterns reach high levels during TM practice after a few months practice, but that progressive changes in EEG patterns are seen in activity after the meditation session, reflecting experience-related neuroplasticity integrating the meditation experience with daily activity (Travis et al. 2001).

The TM technique can be understood as procedural knowledge rather than declarative knowledge. Learning TM is analogous to learning to ride a bike. A parent teaches their child to ride a bike by running along with a hand on the seat and handlebars, and the child gets a feel for riding the bike. Lengthy lectures—declarative knowledge—do not help a child learn to ride a bike. Similarly, an individual experiences automatic transcending for the first time during

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[1] At the first posttest, subjects were told: "Sit with eyes closed for 10 min, or practice the Transcendental Meditation technique for 10 min, if you have been instructed." In this way, the researcher recording the data did not know if subjects were resting with eyes closed or were practicing the Transcendental Meditation technique.

personal instruction, guided by a trained teacher. Once having had that experience, individuals come together for 1-h meetings, over the next 3 days, to more fully understand the process of transcending during TM practice.

Data selection

A 60-sec artifact-free period was selected in the first 3 min of the 10-min eyes-closed periods during pretest (eyes-closed rest) and during the posttest TM period for the experimental group and eyes-closed rest for the control group. Previous research reports that brain patterns in the first minute of TM practice are similar to those in the middle and at the end of the TM session (Travis and Wallace 1999). Thus, brain patterns in the first 3 min should be representative of brain patterns during the 20-min TM session.

Data analysis

The data were analyzed with Brain Vision Analyzer software. The 60 sec artifact-free data were re-referenced to averaged left and right ears, to compare with previous TM research; digitally filtered in a 2.0–50 Hz band with a 48 dB roll off; and fast Fourier transformed in 2-sec epochs, using a Hanning window with 10% onset and offset. Power (uV^2) was calculated from 2–50 Hz at the 32 recording sites. Coherence, the absolute value of the cross-correlation function in the frequency domain, was calculated for the 496 possible combination pairs of 32 recording sites.

Coherence analysis

Coherence estimates were calculated in six frequency bands: theta (5–7.0), alpha1 (7.5–10.0 Hz), alpha2 (10.5–12.5 Hz), beta1 (13–20 Hz), beta2 (20.5–30 Hz), and gamma bands (30.5–50 Hz); and averaged in three spatial coherence averages representing increasing inter-electrode distances—frontal (AF3-F3, AF3-FC1, AF4-F4, AF4-FC2), frontal–central (AF3-C3, AF3-CP1, AF4-C4, AF4-CP2), and frontal-parietal pairs (AF3-P3, AF3-PO3, AF4-P4, AF4-PO4)—and in frontal (AF3-AF4, F3-F4, FC1-FC2) and parietal midline interhemispheric coherence (CP1-CP2 P3-P4, PO3-PO4).

Power analysis

Power estimates were analyzed in two ways. First, lateral asymmetry was calculated in the alpha band (8–12 Hz) and averaged in three left-hemisphere sensors—F3, AF3, and F7—and three right-hemisphere sensors—F4, AF4, and F8. Frontal alpha power asymmetry has been linked to positive emotions (Davidson et al. 1990, 2000; Davidson 1992). To calculate lateral asymmetry, we followed the procedure used by Davidson, first log-transforming power estimates and then calculating log-transformed right power minus log-transformed left power (Davidson et al. 2003).

Power estimates were also grouped into seven frontal (AF3, F3, FC1, Fz, AF4, F4, FC2) and seven parietal (PO3, P3, CP1, Pz, P4, CP2, PO4) spatial averages. Since power is not normally distributed, the power estimates were transformed to log-power before analysis.

eLORETA

LORETA was developed at the KEY Institute for Brain-Mind Research at the University of Zurich (Pascual-Marqui et al. 1994) to compute the 3D intracerebral distribution of sources of scalp-recorded electrical potentials. Two refinements of this method have been released: first, sLORETA (standardized Low Resolution Electromagnetic Tomography), which used standardized current density to calculate intracerebral generators (Pascual-Marqui et al. 2002) and recently eLORETA (exact Low Resolution Electromagnetic Tomography), which does not require standardization for correct localization (Pascual-Marqui 2007). Both sLORETA and eLORETA have low resolution but zero localization error in the presence of measurement and biological noise (Pascual-Marqui et al. 2002; Pascual-Marqui 2007). The current implementations of sLORETA and eLORETA use a realistic head model calculated by Fuchs (Fuchs et al. 2002) and electrode coordinates provided by Jurcak (Jurcak et al. 2007).

The 60-sec artifact-free periods were exported in ASCII format from the Brain Vision software for eLORETA analysis. The steps of eLORETA analysis include (1) computing EEG cross-spectra from the raw recordings using 2 sec windows with the same six frequency bands used in the spectral analysis; (2) computing cortical generators of surface oscillatory activity using the cross-spectra; and (3) calculating *t*-test differences between conditions for each cortical voxel normalizing by frequency. Normalizing by frequency is similar to relative power in spectral analysis. A voxel in eLORETA was considered significant if it and its six nearest neighbors (top, bottom, sides, front, and back) differed significantly at the $P < .0005$ (two-tailed alpha level) between the two conditions. The eLORETA output program specifies the Brodmann areas (BA) that are reported for sources of activation.

Statistical analysis

MANCOVAs of pre-post difference scores, covarying for pretest scores, were used to test condition differences in coherence, log-power, and lateral asymmetry. The SPM statistical software in eLORETA was used to conduct pretest analyses (independent *t*-tests) and posttest analyses (independent *t*-tests).

Results

Of the 50 students who were pretested, 38 students were posttested. Pretesting stretched over 3 weeks. In contrast, the posttest was recorded during the week before final examination. This contributed to scheduling conflicts. Of the twelve students who missed the posttest, seven did not respond to calls for scheduling EEG recordings; one came to several advanced meetings but did not come in for posttesting; three felt that they did not have sufficient time to meditate twice a day and so dropped out of the study; and one never attended instruction or assessment meetings after completing pretesting. A similar number of men and women dropped out of the study (7 men and 5 women) and equal number (six) from both groups.

Baseline analysis

A MANOVA of initial group differences was conducted on age and baseline means for coherence and power for the 12 students who dropped out of the study, and the 19 students in each of the TM and control groups. The omnibus *F*-tests yielded no significant differences in age (Wilks' Lambda $F(2,47) = 1.6$, ns), coherence (all Wilks' Lambda $F < 1.0$), or power (all Wilks' Lambda $F < 1.0$).

Pretest/posttest differences

Figure 1 presents 6 sec of raw EEG from an eyes-closed (left) and TM session (right) referenced to linked ears. This figure presents the 19 sensors in the 10–20 system, selected from the 32 sensors recorded. Fewer sensors are displayed to simplify the pictures. This figure shows qualitative differences that are quantified in the later analyses. As seen in this figure, closing the eyes resulted in well-known posterior alpha. In contrast, TM practice is marked by global alpha bursts of similar amplitude over most anterior and posterior brain areas.

MANCOVA of pre-posttest differences of coherence

MANCOVAs of pretest–posttest differences in coherence, covarying for pretest coherence, yielded significant main effects for the TM group: (1) significantly higher frontal and parietal inter-hemispheric alpha1 coherence ($F(1,37) = 4.4$, $P = 0.045$; $F(1,37) = 4.3$, $P = 0.048$); (2) significantly higher frontal- and frontal-central beta2 coherence ($F(1,37) = 4.2$, $P = 0.050$; $F(1,37) = 4.2$, $P = 0.049$); and (3) a trend for higher frontal interhemispheric beta 1 coherence ($F(1,37) = 3.7$, $P = 0.064$). As seen in this table, higher beta2 coherence resulted more from decreases in coherence during eyes-closed rather than increases during TM practice.

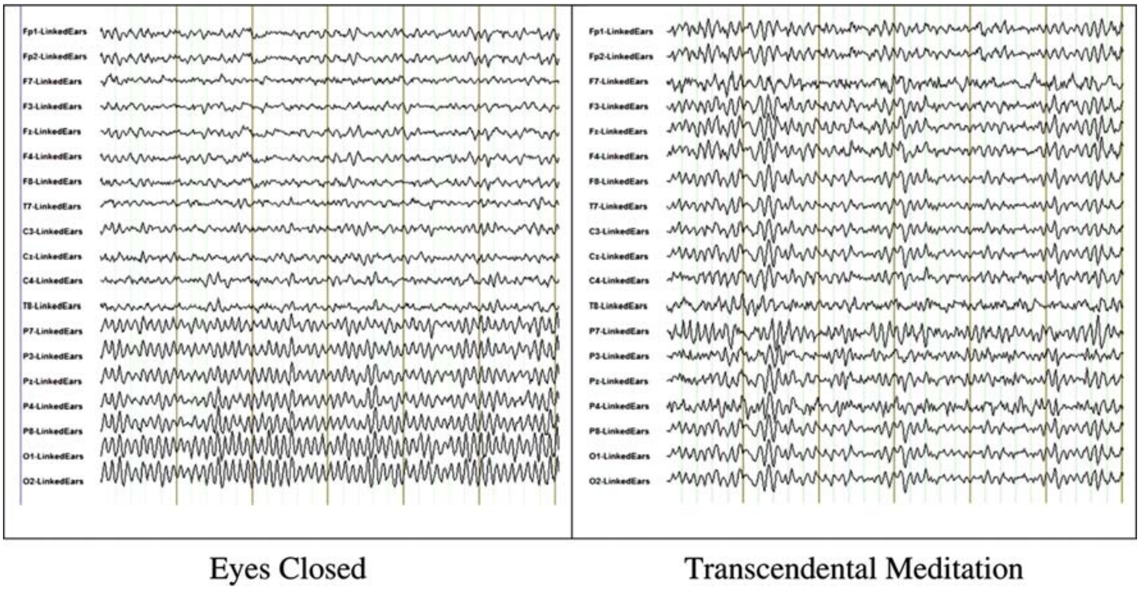

Fig. 1 Raw EEG tracings during eyes closed rest (*left*) and Transcendental Meditation practice (*right*). These figures present 19 tracings in the 10–20 system over 6 sec during eyes-closed rest and TM practice referenced to linked ears. The top tracings are from frontal sensors; the middle tracings are from temporal and central sensors; the bottom tracings are from parietal and occipital sensors. Note the high-density alpha activity in posterior leads during eyes-closed rest, and the global alpha bursts across all brain areas during Transcendental Meditation practice

Table 1 Posttest-pretest differences, standard deviations, and partial eta squared (η2) for five coherence factor averages in six frequencies. Positive difference scores indicate higher coherence at posttest

	Frontal–frontal coherence		Frontal–central coherence		Frontal–parietal coherence		Frontal inter-hemispheric coherence		Parietal inter-hemispheric coherence	
	Diff	η2	Diff	η2	Diff	η2	Diff	η2	Diff	η2
Theta2										
TM	0.05 (0.18)	0.03	0.04 (0.09)	0.01	0.01 (0.05)	0.01	0.08 (0.16)	0.08	0.04 (0.12)	0.02
Control	0.00 (0.21)		0.04 (0.10)		0.01 (0.05)		0.04 (0.16)		0.02 (0.12)	
Alpha1										
TM	0.02 (0.15)	0.03	0.02 (0.10)	0.03	−0.01 (0.06)	0.03	**0.06 (0.15)**	**0.12**	**0.06 (0.10)**	**0.12***
Control	−0.00 (0.21)		0.01 (0.10)		−0.00 (0.05)		**0.01 (0.19)**		**−0.01 (0.12)**	
Alpha2										
TM	−0.01 (0.15)	0.02	0.00 (0.10)	0.03	−0.02 (0.10)	0.02	0.03 (0.17)	0.01	−0.01 (0.12)	0.01
Control	−0.02 (0.17)		−0.00 (0.06)		−0.02 (0.06)		0.03 (0.15)		0.02 (0.10)	
Beta1										
TM	0.00 (0.20)	0.08	0.01 (0.05)	0.03	−0.00 (0.02)	0.05	**0.04 (0.14)**	**0.11**	0.03 (0.09)	0.09
Control	−0.01 (0.17)		0.00 (0.04)		−0.00 (0.01)		**0.01 (0.12)**		−0.01 (0.11)	
Beta2										
TM	**0.00 (0.17)**	**0.12**	**0.01 (0.03)**	**0.12**	0.00 (0.01)	0.01	−0.01(0.08)	0.07	0.01 (0.11)	0.06
Control	**−0.03 (0.15)**		**−0.01 (0.02)**		−0.00 (.01)		0.00 (0.10)		−0.03 (0.10)	
Gamma										
TM	0.00 (0.17)	0.06	0.02 (0.04)	0.05	0.02 (0.03)	0.04	0.01 (0.11)	0.04	0.01 (0.17)	0.07
Control	−0.02 (0.16)		0.00 (0.04)		0.00 (0.02)		−0.01(.10)		−0.06 (0.17)	

Note TM practice was characterized by higher frontal and parietal inter-hemispheric alpha1 frontal coherence; higher frontal–frontal and frontal–central beta2 coherence; and a trend for higher frontal inter-hemispheric beta1 coherence. Significant coherence factor averages have been bolded for easy identification

Table 1 presents the posttest–pretest coherence differences, standard deviations and partial eta squared (η2) for coherence in the six frequency bands. Partial eta squared (η2) is the power statistic derived from F-tests using SPSS. Partial eta squared is the variance accounted for, similar to r^2. In this table, positive difference scores indicate higher coherence during TM practice. Significant group differences have been bolded in the table.

Comparison of EEG Log-power

Pretest–posttest log-power

A MANCOVA was conducted on pretest/posttest difference scores for frontal and parietal log-power, co-varying for pretest scores. TM practice was characterized by significantly *higher* alpha1 frontal log-power ($F(1,37) = 4.1$, $P = 0.05$), and significantly *lower* beta1 and gamma frontal ($F(1,37) = 4.7$, $P = 0.037$; $F(1,37) = 4.5$, $P = 0.041$) and parietal log-power ($F(1,37) = 5.2$, $P = 0.03$; $F(1,37) = 5.6$, $P = 0.025$).

Table 2 presents the means, standard deviations and partial eta squared (η2) for posttest–pretest log-power for the two groups in the six frequency bands in the frontal and parietal leads. Significant group differences are bolded.

Lateral asymmetry differences

Lateral asymmetry was calculated as log-transformed right power minus log-transformed left power. Thus, increased activation (lower alpha power) in the left hemisphere or decreased activation in the right hemisphere would lead to positive lateral asymmetry values. In this study, lateral asymmetry values were positive and similar in both groups at pretest and posttest. A MANCOVA of group differences in lateral asymmetry, co-varying for pretest values, did not yield significant main effects for groups in frontal lateral asymmetry, $F(1,36) = <1.0$, ns. (Experimental: −0.05; Control: 0.14).

Comparison of eLORETA patterns

Initial differences at pretest

There were no significant intra-cortical sources identified by eLORETA that distinguished the two groups at pretest.

Pre-/posttest differences

Significant intra-cortical sources of EEG activity were seen during TM practice in alpha1 and during eyes-closed rest in

Table 2 Means, standard deviations, and partial eta squared ($\eta 2$) for posttest–pretest difference scores in log-power in the six frequency bands in the frontal and parietal cortices

Frequency	Group	Frontal		Parietal	
		Posttest–pretest log power	$\eta 2$	Posttest–pretest log power	$\eta 2$
Theta2	Experimental	0.27 (0.39)	0.01	0.04 (0.49)	0.01
	Control	0.20 (0.51)		0.16 (0.55)	
Alpha1	Experimental	**0.18 (0.41)**	**0.12**	−0.11 (0.60)	0.02
	Control	**−0.06 (0.45)**		0.15 (0.76)	
Alpha2	Experimental	−0.13 (0.60)	0.04	−0.11 (0.82)	0.013
	Control	0.16 (0.37)		−0.04 (0.55)	
Beta1	Experimental	**−0.04 (0.28)**	**0.14**	**−0.11 (0.33)**	**0.15**
	Control	**0.20 (0.42)**		**0.18 (0.34)**	
Beta2	Experimental	−0.07 (0.35)	0.11	−0.12 (0.33)	0.05
	Control	0.21 (0.44)		0.08 (0.49)	
Gamma	Experimental	**−0.06 (0.89)**	**0.13**	**−0.15 (0.58)**	**0.16**
	Control	**0.36 (0.97)**		**0.24 (0.92)**	

Note A positive difference indicates higher log-power at posttest. TM practice was characterized by significantly *higher* frontal alpha1 log-power and significantly *lower* frontal and parietal beta1 and gamma log-power. Significant differences are bolded for easy identification

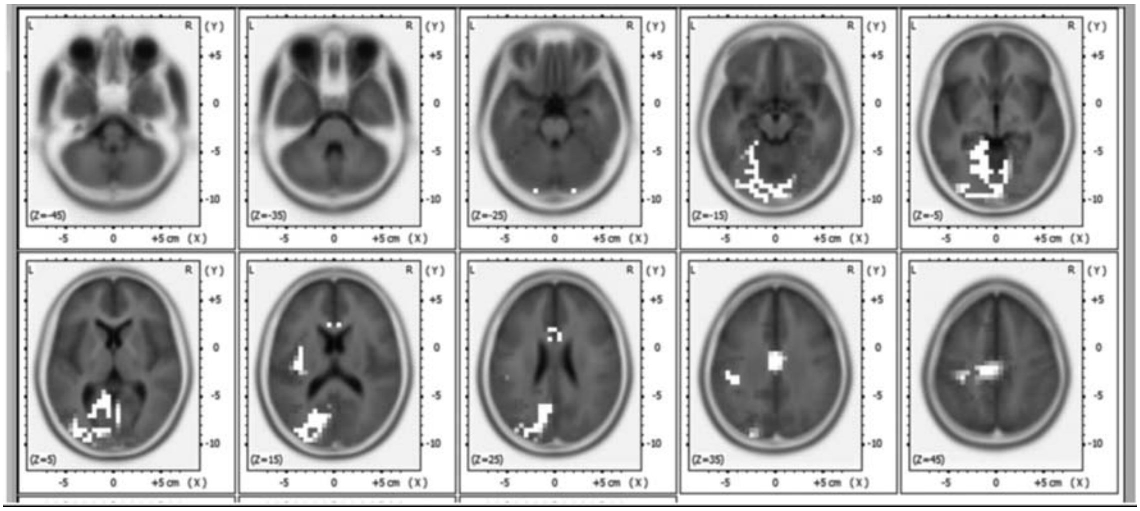

Fig. 2 eLORETA tomographical images of significance differences between eyes-closed rest and TM practice. A white area indicates cortical source during TM practice compared to eyes-closed rest. TM practice was characterized by generators of alpha1 in anterior (BA 33), dorsal (BA 24), and posterior cingulate gyri (BA 30), precuneus (31), and left lingual gyrus and parahippocampus (BA 18, 19). Eyes closed rest was characterized by significant intra-cortical generators of beta2 in right lingual gyrus (BA 18, 19). The Brodmann's areas are assigned by the eLORETA software. Displayed sections are calculated at 10-mm slices from $z = -45$ to $z = 45$

beta2. Figure 2 presents eLORETA tomographical images of significance differences ($P < .0005$) between eyes-closed rest and TM conditions in 10-mm slices from $z = -45$ to $z = 45$. A white area indicates a significant source of surface EEG in that area during TM practice compared to eyes-closed rest. TM practice was characterized by significant generators of alpha1 in anterior (BA 33), dorsal (BA 24), and posterior cingulate cortices (BA 30), precuneus (31), left insula (BA 13), and left lingual gyrus and parahippocampus (BA 18, 19). Eyes closed rest was characterized by significant generators of beta2 in right lingual gyrus (BA 18, 19). (Not shown here.)

Discussion

This 10-week random assignment longitudinal study revealed significant brain wave differences between eyes-closed rest and TM practice in coherence, power, and eLORETA activation patterns. These data supported the first hypothesis—frontal alpha1 power and frontal and parietal alpha1 interhemispheric coherence would be higher during TM practice; the third hypothesis—there would be no alpha lateral asymmetry differences between conditions; and the fourth hypothesis—eLORETA activation patterns would distinguished TM practice from eyes-closed rest. The second hypothesis was partially supported. Beta1 and gamma frontal and parietal log-power were lower during TM practice. However, beta2 frontal and frontal–central intra-hemispheric coherence were higher during TM compared to rest. These beta2 coherence differences appeared to result from coherence decreases during eyes-closed rest rather than coherence increases during TM. Also, there was only a trend for higher beta1 inter-hemispheric frontal coherence. With these caveats, this is the first reporting higher beta coherence during TM practice.

Consideration of brain patterns during Transcendental Meditation practice

Alpha1 power, coherence, and eLORETA sources distinguished TM practiced from eyes-closed rest in this random assignment study. Alpha activity has been associated with cortical idling (Pfurtscheller et al. 1996) and is correlated with lower posterior cerebral metabolic rate during eyes-closed rest in visual areas (Oakes et al. 2004).

However, alpha1 may represent more than cortical idling. Higher frontal alpha has been reported during tasks involving internal focus. So-called paradoxical alpha is reported during internally directed attentional tasks such as imagining a tune compared to listening to the same tune (Cooper et al. 2006). Alpha activity may represent inner wakefulness—the ground for organizing outer experiences. For instance, when solving a problem by intuition or insight, alpha activity increases first followed by gamma activity when the idea comes to mind (Kounios and Beeman 2009). Cross frequency coherence—the synchrony between alpha, beta and gamma—increases with higher cognitive load on a continuous mental arithmetic tasks (Palva et al. 2005). Cross frequency coherence is considered important for integrating anatomically distributed processing in the brain (Palva et al. 2005).

eLORETA patterns distinguishing TM practice

eLORETA calculates deep cortical generators of surface EEG activity, constraining the sources to known gray matter volumes. During TM practice, cortical sources of alpha1 were located in cingulate and precuneus circuits. These midline circuits activated during TM practice overlap those of the DMN (Raichle et al. 2001), which has been defined as a fundamental or "intrinsic property of the brain" supporting extrinsic, localized modes of cognitive processing (Fox and Raichle 2007; Raichle and Snyder, 2007). Since activation in these brain areas was higher during TM compared to eyes-closed rest, the experience of contentless thought with continued self-awareness during TM practice must be different from autobiographical or mind-wandering thoughts. It is possible that TM experiences may be as foundational to the eyes-closed resting default state, as eyes-closed rest is to extrinsic, localized modes of cognitive processing. Future research using PET imaging is needed to definitively address DMN activation during TM practice.

Brain patterns during different meditation practices

Readers of the papers in this special issue may note that different meditation techniques involve different procedures and result in different inner experiences and different brain states. For instance, while alpha lateral asymmetry was not different during TM practice, significant central and temporal lateral asymmetries have been reported during Mindfulness meditation (Davidson et al. 2003). While beta1 and gamma log-power were lower during TM practice, a 30-fold increase in gamma power and gamma synchrony have been reported during Tibetan Buddhism meditation (Lutz et al. 2004). Last, while higher alpha1 power and coherence are reported during TM practice, higher theta power and coherence are reported during Sahaja Yoga concentration meditation (Aftanas and Golocheikine 2001; Aftanas and Golocheikine 2002).

The articles in this volume should encourage the scientific community to define a core set of physiological variables, including brain imaging along with EEG power and coherence to better characterize brain states produced by different meditation traditions. The resulting meditation physiological profiles could be used to better understand effects and potential clinical applications of different meditation practices. These physiological profiles could shed light on the relation between meditation experiences and the default mode of brain function.

Conclusion

In this random assignment study, patterns of alpha1 power, coherence, and eLORETA distinguished TM practice from eyes-closed rest. The areas of alpha1 activation during the TM practice overlapped areas in the DMN, suggesting a relation between TM experiences, self-referential experiences and intrinsic default modes of brain function. The subjective experiences during Transcendental Meditation practice may be as foundational to the eyes-closed resting default state, as eyes-closed rest is to normal task-oriented cognitive activity.

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